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RESEARCH AND DEVELOPMENT OF AN ADVANCED PERSONAL LOAD CARRIAGE MEASUREMENT SYSTEM: Phase IV: Section C

Phase II of a Biomechanical Model For Load Carriage Assessment

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RESEARCH AND DEVELOPMENT OF AN ADVANCED PERSONAL LOAD CARRIAGE MEASUREMENT SYSTEM:

Phase IV: Section C
Phase II of a Biomechanical Model For Load Carriage Assessment

by

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Executive Summary

The backpack is the military personnel's device of choice for load carriage. Until recently, little was done in Load Carriage System (LCS) research and development. However, the recent recreational boom has seen the basic backpack design undergo much manipulation. The most notable change has been the addition of a load bearing waist belt.

Deciding if design changes were effective usually meant building a prototype and obtaining human feedback on various characteristics. This method is costly and time consuming and the results are subjective. Defense and Civil Institute for Environmental Medicine requires a more efficient and effective means of evaluating preliminary pack designs.

Therefore, the purpose of this study was to develop a personal load carriage system design tool. An appropriate evaluation tool should enable designers to input pack parameters and receive an objective measure of the pack's effectiveness. Pack parameters include the pack dimensions, weight, centre of gravity, and location of shoulder straps, waist belt, and lumbar pad. The objective evaluation consists of two body reaction forces known to relate to pack acceptability scores. With knowledge of the body reaction forces one gains an understanding of comfort, and can compare potential prototypes.

A statically determinate model of the pack-person interface was developed to include the design parameters of interest and the evaluated body reaction forces. From the design inputs, the model determines the remaining pack geometry. The equilibrium equations and pack variable relations determine the tension of the pack straps, while the force couples between the torso and the pack are used to calculate the body reaction forces.

Stevenson et. al. (1995) determined human pain perception levels for the shoulder and lumbar contact forces. These values were used to provide an understanding of the degree of the body reaction forces.

To validate the effectiveness of the design tool, six packs were tested on a human form jig. The jig was instrumented to measure the required body reaction forces. The required design parameters of each pack were measured and used as inputs to the model. The model detailed the way in which each pack was to be setup and three independent data sets were collected. The data showed that the design tool was able to predict outputs to within 10% of the measured values.

Despite the fact that the body reaction force predictions were validated, reservations exist about the evaluative ability of the design tool. It is unclear which of the body reaction forces has the greatest impact on the acceptability rating of a pack. Therefore, it becomes difficult to differentiate between a pack which has a high shoulder reaction force and low lumbar force, from a pack with low shoulder forces and high lumbar forces. The ability of human subjects to detect changes in the body reaction forces is unclear.

The vertical force contribution of the lumbar pad and the waist belt is not well understood. The total lift of the waist belt/lumbar pad complex is well understood and was validated. However, the exact contribution of each element is unclear.

In order to work with the limitations of this design tool the outputs should be used to understand the trends associated with parameter variation. As well, designs that produce body reaction forces above the pain perception levels should be considered inappropriate.

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1. Introduction

Many different devices exist to improve the load carriage capability of humans. History has shown the backpack to be the most common choice of military personnel. In this capacity, the pack's basic design underwent very little change. However, motivated by corporate marketing, the recent recreational boom has increased innovations of the basic backpack design. Only by understanding the effects of these changes can further design advances be made. Until now advances in pack design came from subject evaluation of prototype systems. Two major drawbacks exist with this approach. First, creating prototypes and working with human subjects makes this method expensive and time-consuming. Second, the data collected using human subjects are subjective in nature. More efficient methods could be developed in order to facilitate advances in pack design. The Defense and Civil Institute for Environmental Medicine (DCIEM) requires such an approach to Personal Load Carriage System (LCS) design. Although human subjects would still be required to evaluate prototypes during the final phases of a load carriage system design, an objective and inexpensive approach was required during the initial phases. This design tool provides instant feedback about potential designs and eliminates unnecessary costs and ambiguity. This tool allows for input of pack design parameters and effectively outputs relevant body reaction forces. These body reaction forces, when compared to pain perception levels, can be used to evaluate packs. The important elements for creation of a load carriage system design tool are:

- Identify the important parameters associated with the pack - person interface.
  Through literature review understand the pack design parameters that significantly contribute to comfort and functionality.

- Develop a statically determinate biomechanical model of a typical LCS.
  Using the parameters identified above, create a model that will use design parameters as inputs and provide body reaction forces as outputs. The model can then be used during the design phase to understand the impact each design change has on the pack user.

- Validate the biomechanical model.
  By instrumenting a 50th percentile human mannikin with two six-degree of freedom load cells, body reaction forces can be measured. Five sample packs are tested and the results are compared with the biomechanical model predictions. A prediction error smaller than ±10% on each measure will be required to deem the model valid.

- Determine the pain perception levels for model outputs.
  Through literature review, pain perception levels for each of the model outputs will be determined. Pain perception levels represent ceiling values for each of the model outputs.

- Develop a computer spreadsheet that allows a user to interface with the biomechanical model. A basic window based spreadsheet will accept specific design parameters and display the model output parameters. The result will be a preliminary evaluation of the LCS prototype design.

2. Biomechanical Model Development

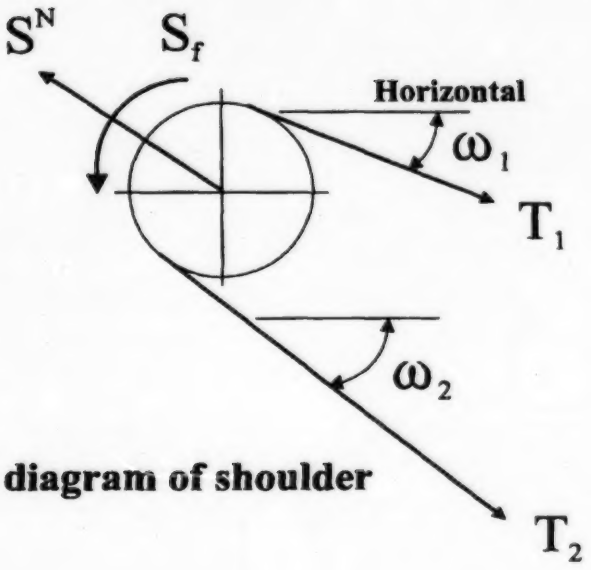
2.1. Shoulder Based Model

The biomechanical model is the basis of the design tool. As increased understanding was gleaned, the model has evolved over time with input from several researchers. The original model stems from the simplest backpack design, a bag with shoulder straps. Stevenson et. al. (1995) developed the original model shown in Figure 1 as part of the Queen's University contract with DCIEM. The notation in the current report has been modified, to remain consistent with the newer models. MacNeil (1996) continued the model development by determining the relation between the tensions in the upper and lower portions of the shoulder straps, T1 and T2 respectively, and validating the work of Stevenson et al. By working through this original model from the beginning, a more complete understanding of the current model will be achieved. Motivation for additions to the shoulder-based model will also become clearer.

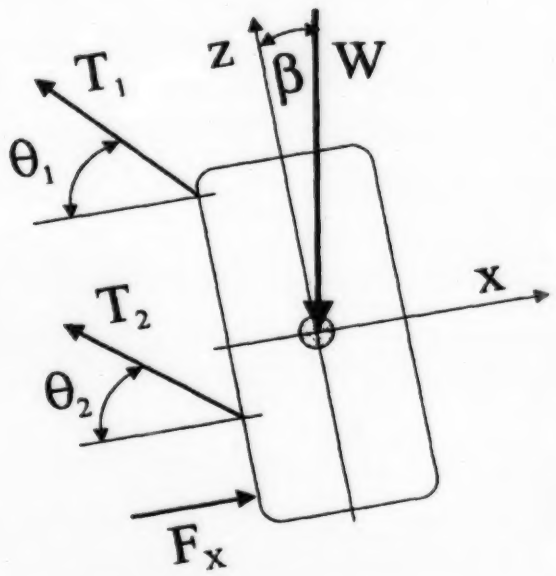
Figure 2 outlines the basic features of a shoulder based pack, a bag held onto the body with a pair of shoulder straps. In a simplified sense only three force couples exist. The upper and lower segments of the shoulder straps hold the load carriage system vertically, and against the body while their couples apply force to the shoulder. The back experiences a third force equal to the summed horizontal components of the shoulder strap forces, thus maintaining equilibrium.

The forces that act on the pack produce a net moment of zero about the centre of gravity of the pack. Figure 1 illustrates a basic shoulder based pack in static equilibrium, where ΣF_X, ΣF_Z, and ΣM_{cog} all equal 0. The pack is inclined, as the normal stance under a heavy load is a slight forward lean to maintain the centre of mass over the feet. A relationship also exists between the upper and lower shoulder straps, with tensions T1 and T2 respectively. MacNeil (1996) modeled this relationship as a rope around a pulley (Equation 1), where μ_s is the friction factor around the shoulder, and α is the wrap angle. He also validated that the contact of the pack with the person can be simplified as a single point. Using these principles and the static equilibrium equations outlined in Appendix A, the model in Figure 1 was validated (MacNeil, 1996).

$$T_1 = T_2 \cdot e^{\mu_s \alpha} \quad (1)$$



Free body diagram of shoulder



Free body diagram of backpack

Figure 1. Shoulder-supported PLCS model (MacNeil, 1996)

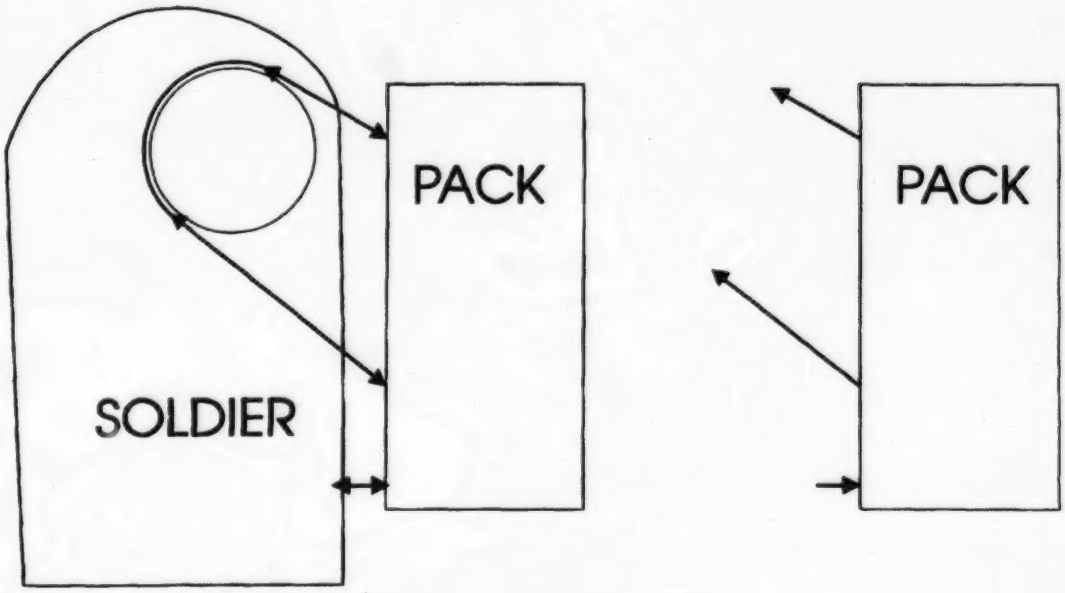


Figure 2. The simple bag and straps representation of a pack

2.2 Additions Required for the Advanced Model

Although the shoulder based model provided an excellent starting position for detailed modeling of a pack, some additions were required. The most obvious addition to the shoulder-based model,was the waist belt. Pack designers use a waist belt system to apportion the weight of the pack between the hips and the shoulders.

Frictional forces at the torso contact points were a second addition to the existing model. MacNeil showed that friction exists around the shoulder but friction exists at all other contact points. In fact, today's designers often use materials to increase the friction between the pack and the user. Therefore, friction will be incorporated into the waist belt and the lumbar pad contact points.

3. The Biomechanical Model

The advanced biomechanical model is developed in stages below, culminating in the full model which integrates all of the elements. The notation is presented in section 3.1.

3.1 Description of variables

Orientation:

X	coordinate along pack depth (positive out from bearer)
Z	coordinate along pack height (positive up)

Pack Container:

W	the force of the mass of the pack
v_X, v_Z	position of Centre of Mass from bearer and bottom of pack respectively
h_X, h_Z	outside dimensions of pack container

Bearer:

d_4	distance from lumbar pad contact centre to shoulder centre
d_5	distance from pack back to shoulder centre
r	radius of shoulder
r_H	radius of hips
β	body lean angle from vertical
γ_L	anatomical lower back angle from vertical
γ_B	anatomical hip angle from vertical

Shoulder straps:

T_1	tension in upper shoulder straps (LHS and RHS summed)
T_2	tension in lower shoulder straps (LHS and RHS summed)
d_1	distance from lumbar pad contact centre to attachment point of upper shoulder strap
d_2	distance from lumbar pad contact centre to attachment point of lower shoulder strap
θ_1	upper shoulder strap angle from plane perpendicular to pack back
θ_2	lower shoulder strap angle from plane perpendicular to pack back
α	angle subtended by contact of strap wrapped around shoulder
μ_S	coefficient of friction of strap on shoulder
S^N	the net force acting normal to the shoulder (LHS and RHS summed)

Waistbelt:

T_3	tension in waistbelt
d_3	distance of lumbar pad contact centre from bottom of pack
T_{3C}	the compressive force that T_3 applies around the hips
T_{3C}^N	the component of T_{3C} normal to the hips
T_{3Cf}	the force of friction due to T_{3C}
F^B_Z	lift provided by waistbelt resting on hips
μ_B	coefficient of friction of waistbelt on hips
t	thickness of waistbelt

Lumbar area:

F_X	reaction force of lower back on pack in X-direction
F_X^N	the component of F_X normal to the lower back
F_{Xf}	the force of friction due to F_X
F^L_Z	lift on the pack from lumbar pad resting on lower back
μ_L	coefficient of friction of lumbar pad on lower back
F_Z	total lift force at lumbar contact point of pack

3.2. The Elements of F_z

F_z represents the lift in the Z direction from the waist belt / lumbar pad complex in the equilibrium equations. Although the exact contributions of F^B_z and F^L_z cannot be individually determined, F_z can be validated. One assumption has been made regarding the contribution of F^B_z and F^L_z to F_z. The assumption lies in deciding which element is used to its maximum ability.

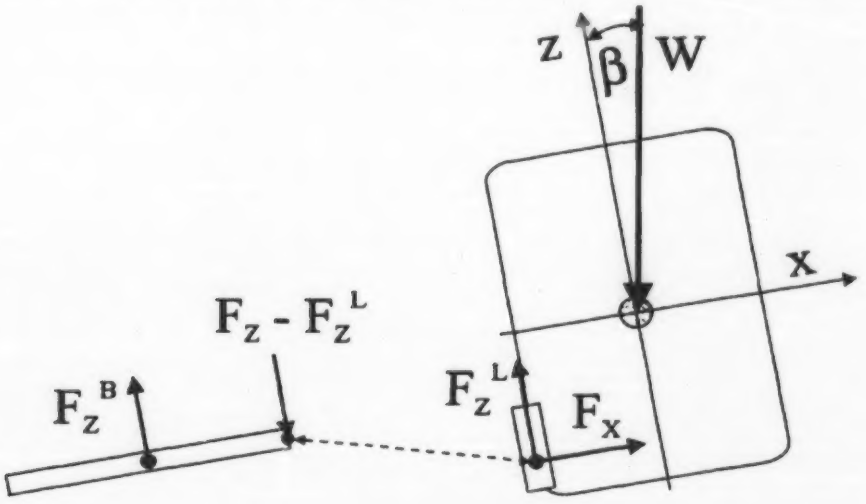


Figure 3. The elements of F_z

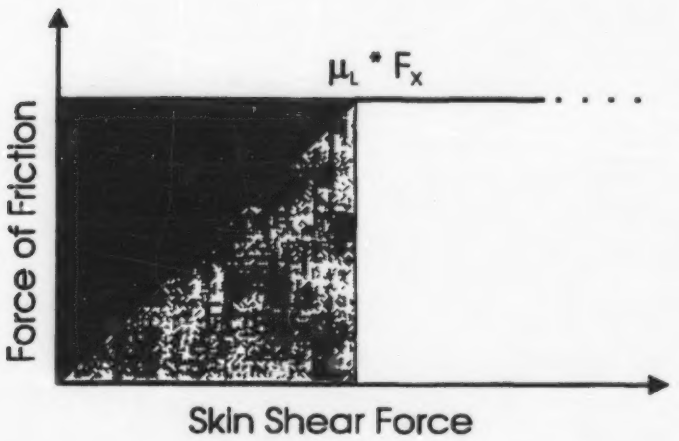


Figure 4. The ability of Friction

Figure 4 illustrates the ability of friction. Because the force of friction is only as large as it needs to be, (up to a maximum level, decided by the normal force and the coefficient of friction) the tension in the waist belt can be altered to vary the contribution of F^B_z and F^L_z. For example, assume that the static equilibrium solution to a particular load results in F_z being 100 N. The friction due to the normal reaction force F_x at the lumbar region alone, could produce an F^L_z value of 100 N. However, with the waist belt tightened to such a degree that F^B_z is 40 N, then F^L_z is assumed to be only 60 N, despite that fact that it could be 100 N. When the waist belt is loosened F^B_z decreases and F^L_z increases. When the waist belt is removed completely F^L_z increases to its 100 N maximum. In order to decide what contribution each makes it was assumed that F^L_z acts to its full potential and then the waist belt is tightened to account for the remainder of F_z.

3.3. The Waist

To model a waist belt, an understanding and simplification of the anatomical waist had to be achieved. Figure 5 shows a transverse section of the simplified waist used in the modeling process. The major assumptions are that the low back and abdominal areas are considered flat-faced sections and the hips are considered to be two semicircles. Although these assumptions seem simplistic when compared to a typical transverse section of a human subject, similarities can be drawn. Furthermore, these simple geometric shapes made future calculations more manageable.

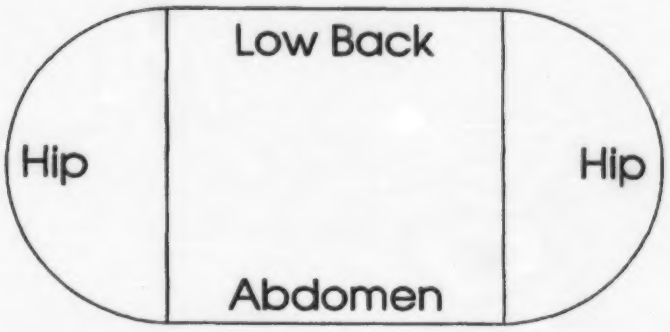


Figure 5. Anatomical simplification of a transverse waist section

One more element of the hips must be understood before the waist belt can be modeled. Human hips lie at a slight angle from vertical and are modeled using a wedge shape. These two simplifications were combined into a three-dimensional model (Figure 6). The hips were modeled as mid sections of a cone while the abdomen was left as a flat-faced surface.

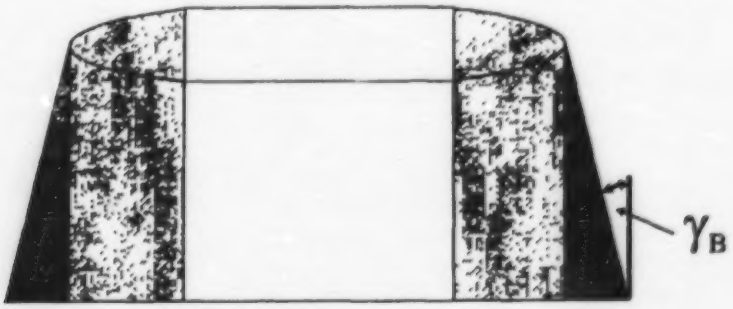


Figure 6. Anatomical angle of the Hips.

3.3.1. The Waist Belt

The waist belt accomplishes the task of supporting pack mass through compression of the waist (Figure 7). Over the hip area the waist belt applies a compression force that transmits lift to the pack through friction and the slight angle of the hips. The friction resists the pack from sliding down the body and the angle of the hips allows for some of the reaction force to transmit directly upward (Figure 8). In order to determine the compression force of the waist belt the two semicircles are combined to make a full circle. The full circle waist belt was then modeled using the hoop stress equation (Equation 2). σ, P, r_H, and t represent the tension in the waist belt, the compression pressure, the average radius of the "hips" circle, and the thickness of the belt respectively. In order to use the hoop stress equation the tension in the waist belt was assumed constant over the whole belt.

$$\sigma_{HOOP} = \frac{P \cdot r_H}{t} \qquad (2)$$

To model the waist belt over the abdomen and the low back a simplification had to be made. The waist belt was assumed to exit the pack parallel to the low back surface (Figure 7). Since the abdomen and the low back are flat-faced surfaces, and the waist belt runs tangent to these surfaces, no compression exists over these areas. Therefore, they can be ignored in the waist belt model.

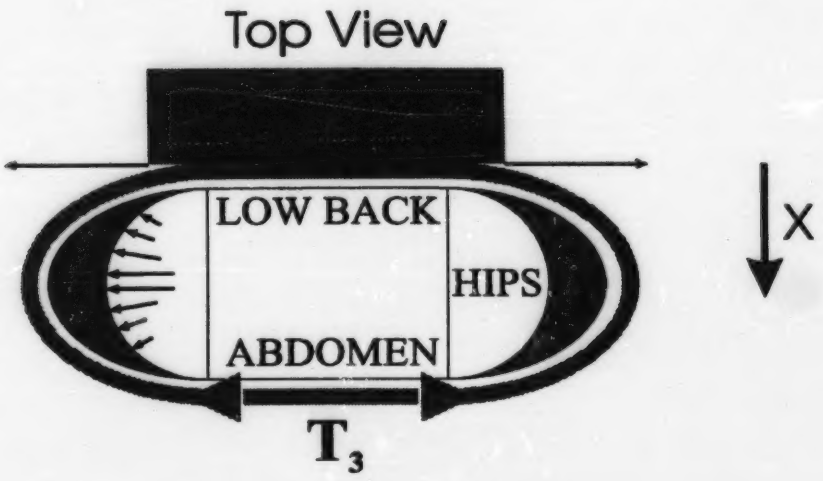


Figure 7. Waist Belt Model in transverse section.

Two other simplifications were important to the development of the waist belt model. First, the nature of the model ensures that the waist belt applies no net horizontal force on the pack (Figure 7). Each side of the waist belt pulled equal and oppositely. Second, the waist belt was assumed to be connected to the pack by means of a pin joint. Therefore, the waist belt transmitted no moment to the pack body. The detailed calculations are provided in Appendix 3.

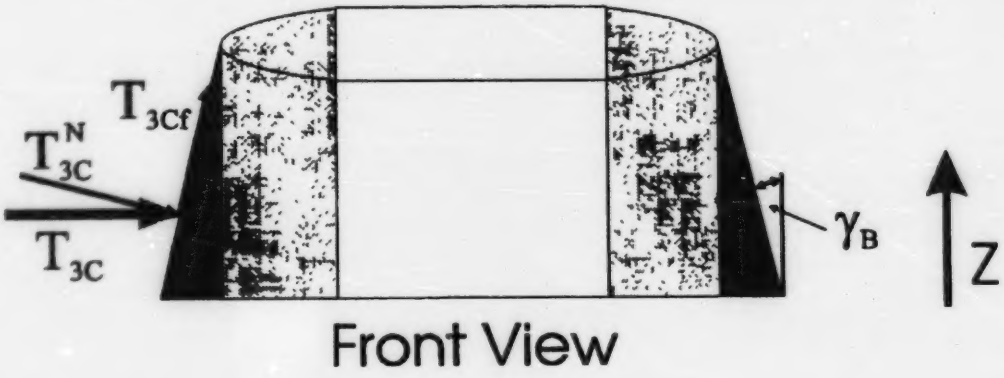


Figure 8. Lift capability of the waist belt

3.4. The Lower Back

Similar to modeling the waist belt, modeling the lumbar pad requires understanding and simplification of the lower back. As noted previously the low back was modeled as a faced surface. However, like the hips the low back has a slight tilt from vertical (Figure 9) and the lumbar pad is designed to exploit this.

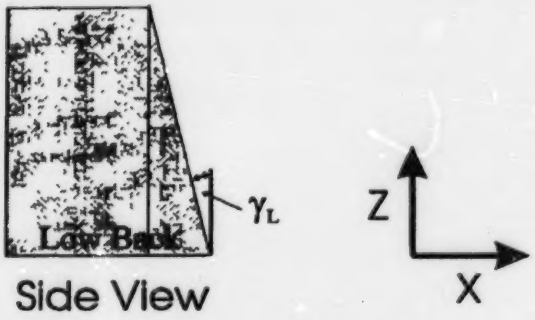


Figure 9. Anatomical simplification of the low back

3.4.1. The Lumbar Pad

Although the waist belt offers no horizontal force to support the pack, the pack equilibrium transmits a force perpendicular to the low back through the lumbar pad, F_X. Like the waist belt this body reaction force applies a vertical lift due to the force of friction and the low back angle γ_L (Figure 10). A detailed calculation of the forces presented in Figure 10 is given in Appendix C.

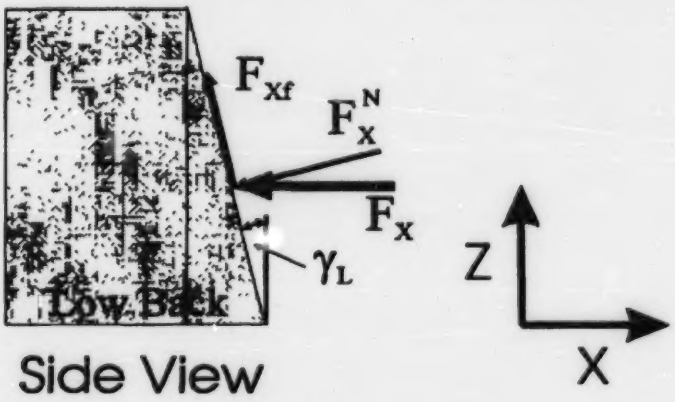


Figure 10. Force application at the low back

3.5. The Pack Model

Combining the original shoulder based model with the waist belt and lumbar pad models, a complete pack model was created. This detailed model can be seen in Figure 11.

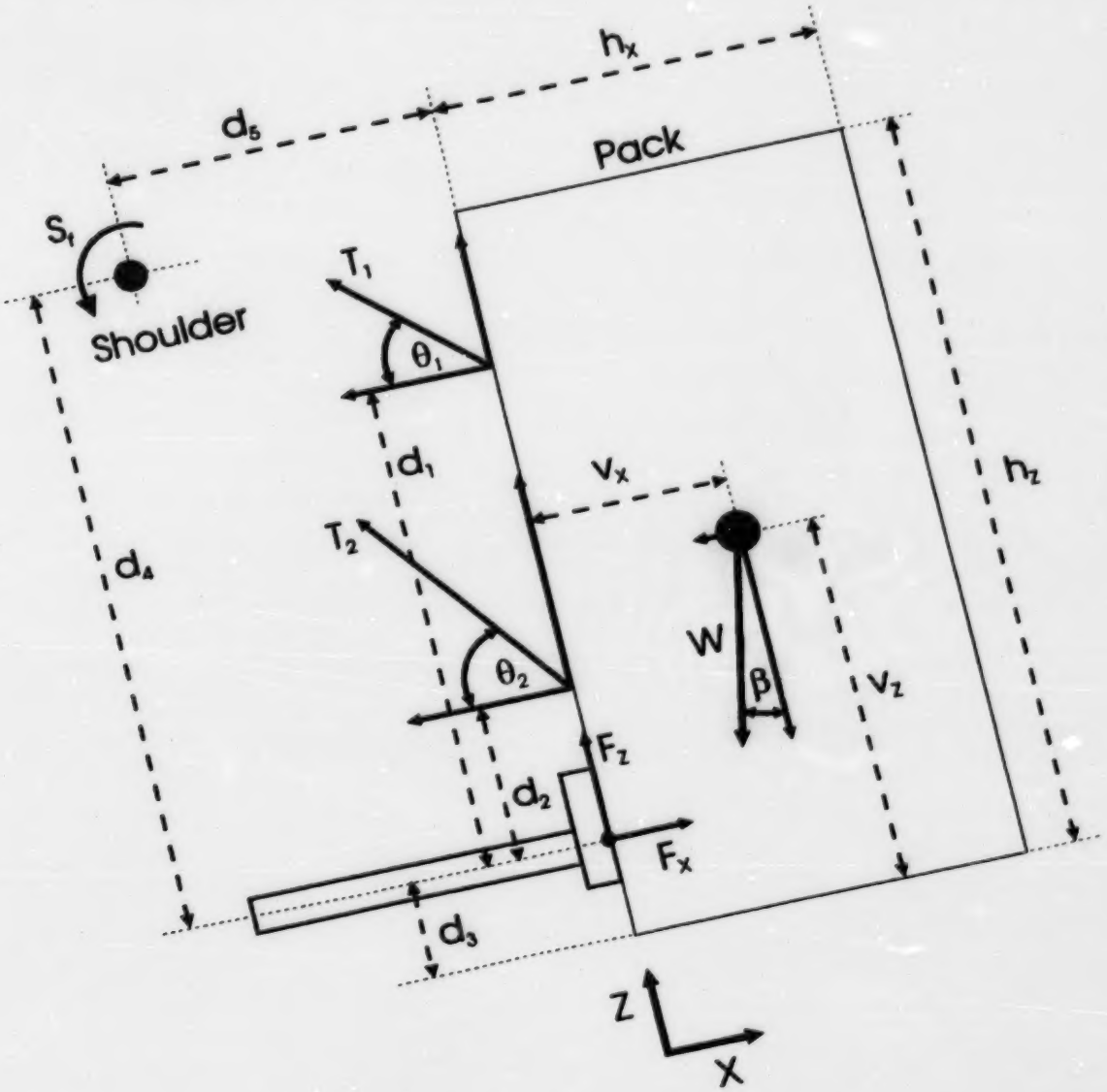


Figure 11. The biomechanical model

3.6. Variable Relations

Many of the variables are mathematically related through geometric or static equilibrium equations. These relations, provided in Appendix B, are used to simplify the expressions.

3.7. Equilibrium Equations

A set of static equilibrium equations was developed for the advanced model. Combining the variable relations outlined in Appendix B with the equilibrium equations revealed a statically determinant model. The resulting system of equations was solved and the body reaction forces were determined.

X-direction Force: $$F_X - T_1 \cdot \cos\theta_1 - T_2 \cdot \cos\theta_2 - W \cdot \sin\beta = 0 \quad (3)$$

Z-direction Force: $$F_Z + T_1 \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2 - W \cdot \cos\beta = 0 \quad (4)$$

Moment about the centre of gravity:

$$F_X(v_Z - d_3) - F_Z \cdot v_X - T_2\cos\theta_2 \cdot (v_Z - d_2 - d_3) - T_2\sin\theta_2 \cdot v_X + T_1\cos\theta_1 \cdot (d_1 + d_3 - v_Z) - T_1\sin\theta_1 \cdot v_X = 0 \quad (5)$$

Using substitution and elimination, the unknowns in the above expressions can be isolated:

$$T_2 = \frac{W \cdot \left[v_X\cos\beta - (v_Z - d_3) \cdot \sin\beta\right]}{e^{\mu_s\theta_1} \cdot d_1 \cdot \cos\theta_1 + d_2 \cdot \cos\theta_2} \quad (6)$$

$$F_X = W\left[\sin\beta + \frac{\left[e^{\mu_s\theta_1} \cdot \cos\theta_1 + \cos\theta_2\right]\left[v_X\cos\beta - (v_Z - d_3) \cdot \sin\beta\right]}{e^{\mu_s\theta_1} \cdot d_1 \cdot \cos\theta_1 + d_2 \cdot \cos\theta_2}\right] \quad (7)$$

$$F_Z = W\left[\cos\beta - \frac{\left[e^{\mu_s\theta_1} \cdot \sin\theta_1 + \sin\theta_2\right]\left[v_X\cos\beta - (v_Z - d_3) \cdot \sin\beta\right]}{e^{\mu_s\theta_1} \cdot d_1 \cdot \cos\theta_1 + d_2 \cdot \cos\theta_2}\right] \quad (8)$$

3.8. Bearer Interface – Body Reaction Forces

After the biomechanical model of the pack was created, the effect the pack had on the body was determined. A free body diagram of a torso was created based on the biomechanical model (Figure 12). The value of each body reaction force came from the force couples associated with the biomechanical model of the pack.

X-direction Shoulder Reaction Force: $S_X^N = T_1 \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2$

Z-direction Shoulder Reaction Force: $S_Z^N = T_1 \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2$

Net Shoulder Contact Force: $S^N = \sqrt{\left(S_X^N\right)^2 + \left(S_Z^N\right)^2}$

Low Back Contact Force: F_X

Transverse Skin Shear at low back: F^L_Z

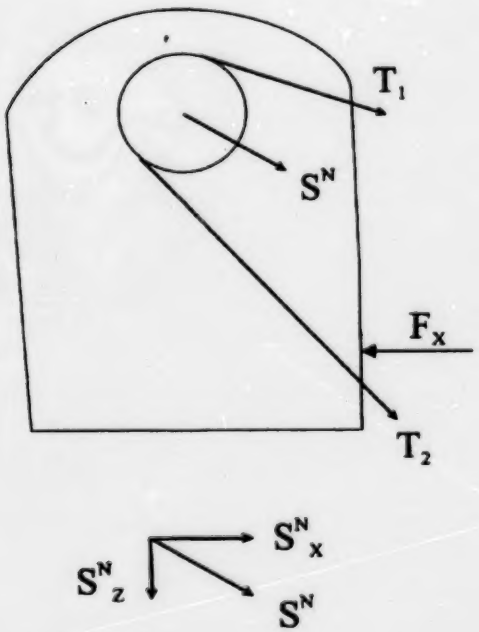


Figure 12. Body reaction force free body diagram

4. The Design Tool

4.1. Relationship Between the Design Tool and the Biomechanical Model

Up to this point the discussion has focused on the biomechanical model of a pack, including the history of the pack model, the additions to the shoulder model, the advanced model, and the equilibrium equations. However, the main goal of this report is to describe the load carriage system design tool. To refresh, a design tool's main purpose is to accept design parameters of a given pack and evaluate that pack.

The first step in moving from the biomechanical model to the design tool was to determine which elements of the model were considered design parameters. The next step was to use the design parameters and the anthropometrics of a 50th percentile user to determine all other geometric properties of the pack. The final step was to apply the remainder of the model, the equilibrium equations, and the variable relations to determine the body reaction forces. The body reaction forces became the means of evaluating the design.

4.2. Inputs to the Design Tool

The current version of the design tool was initialized to default to the anthropometric values for the 50th percentile male, which conforms with the mannikin size for laboratory testing. The other variable considered constant is the bearer lean angle β of 10° from vertical. While wearing a pack of considerable weight each subject tends to lean forward to help balance the load. Past experience with military personnel suggests that 10° is a typical lean angle (Stevenson et al., 1995).

Some elements that the pack designers can control are the dimensions of the pack, and the type of material that the pack is made from, and thus the coefficient of friction. The software user must also input the mass of the pack and the centre of gravity. The default for this latter value is the geometric centre of the pack external dimensions. The variables shown in Figure 13 are part of the input set, as well as the coefficient(s) of friction, and bearer's body characteristics.

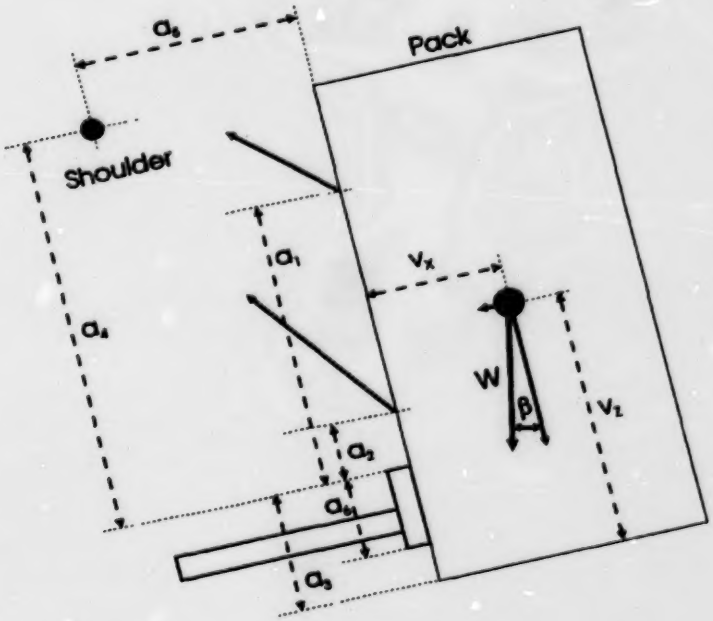


Figure 13. Design tool inputs

4.3. Outputs of the Design Tool

The outputs of the design tool fell into two categories: geometric outputs and body reaction force outputs. The three geometric outputs were design elements that are required as inputs to the model, yet are functions of the design parameters. The two shoulder strap angles were calculated based on the strap positions and the wrap angle resulting from the shoulder strap angles. These three outputs then are used as inputs to the model. These geometric outputs are calculated in Appendix D. A diagram of the outputs can be seen in Figure 14.

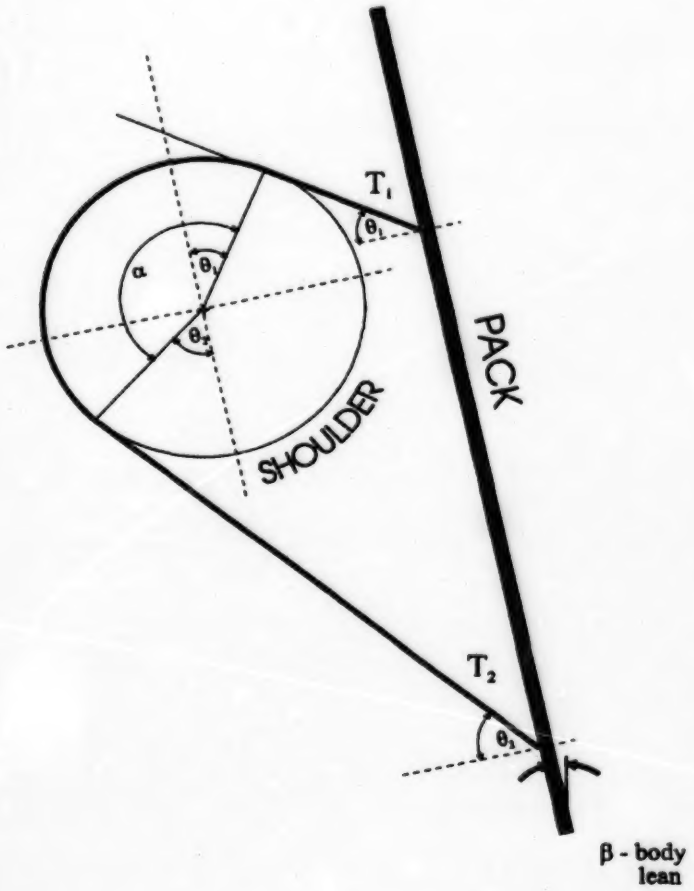


Figure 14. Design tool geometric outputs

The body reaction forces are the principal outputs of the design tool, for use in evaluating a given pack design. These outputs include only the major body reaction forces that have been associated with comfort scores on previous military testing (Stevenson et. al., 1995). The outputs are the shoulder reaction force, both vertical and horizontal, and the low back contact force. The body reaction forces can be seen in Figure 15.

Other factors that have been related to discomfort scores are the contact pressure at the shoulder strap, waist belt, and lumbar pad. However, Rigby (1996) showed that the most prominent pressure values under a shoulder strap were the result of the surface features of that strap. Specific surface features such as buckles and connection points are not a part of the preliminary design phase and as such were omitted from this tool.

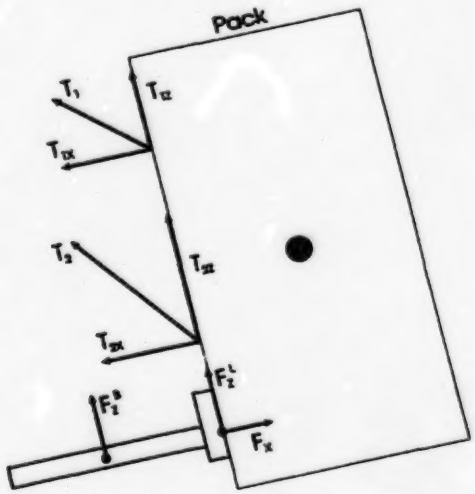


Figure 15. Body reaction force couples – model outputs

4.4. Pain Perception Levels

The human threshold values provide a reference for understanding the nature of the design tool outputs. The limitations of this method for pack evaluation are discussed in section 6.2.

Table 1. Pain perception levels

Evaluation Variable	Pain perception level
Shoulder Force – S^N	289 N
Lumbar Force – F_X	135 N

5. Design Tool Validation

5.1. Testing Jig

The testing jig consisted of a 50th percentile human form mannikin instrumented to record the body reaction forces necessary to validate the load carriage system design tool. The mannikin was also covered with 5mm Bocklite™, a substance used in prosthetics, to represent human skin. The entire jig was fixed to a rotating vice in order to provide forward lean for the mannikin (Figure 16)

Figure 16. Testing Jig

To measure the shoulder reaction forces the mannikin was split at the T10 level of the spinal column and a six degrees of freedom load cell was installed. With this setup and the fact that only the shoulder straps act on the torso above the position of the load cell, the shoulder reaction forces could be measured accurately.

The testing jig was placed on a force platform in order to measure the ground reaction forces. Knowing the ground reaction forces and the shoulder reaction forces allowed for the measurement of F_Z occurring below the torso split.

The Tekscan™ pressure sensing system was used to determine the low back normal contact force, F_X. The Tekscan™ system uses thin, printed, resistive ink sensors. Each 203mm by 76mm sensor is split into a 6x16 cell grid. The electrical resistance of each cell depends on the pressure applied to that cell. That voltage change is calibrated in order to measure the pressure over the area. Tekscan™ recommends that the sensors be calibrated in situ. Because of the position of the sensors on the mannikin such a calibration was not possible. As a result the maximum sensor error may have occurred. Literature shows this error has been found as high as 28% of applied load (Woodburn and

Helliwell, 1996). The accuracy of the F_x measurement was thus bounded by the Tekscan™ system.

In order to measure the strap tensions predicted by the model, Wheatstone bridge strain gauge transducers were inserted into each of the shoulder straps and the waist belt. The in-house designed transducers were found to be extremely linear, ($R^2 > 0.9995$) (MacNeil, 1996) (Figure 17).

Figure 17. Test Setup

5.2. Validation Procedure

In order to determine the accuracy of the biomechanical model predictions, six different packs were tested. Each pack was chosen based on specific criteria so that a representative sample was tested. A description of each pack can be found in Table 2.

Each pack was measured in order to input the appropriate dimensions into the design tool As well each pack was loaded with standard weights and the centre of gravity was determined and input into the model.

Table 2. Description of test packs

Pack ID	Frame Type	Specific Description
Test Pack A	External rigid	Large pack with low friction and full external frame
Test Pack B	Internal flexible	Large pack with large lumbar pad and large friction effect
Test Pack C	Internal frame sheet	Large pack with medium friction and contoured back design
Test Pack D	External flexible	Small pack with full external flexible frame and small friction effect
Test Pack Dru	Internal frame sheet	Medium pack with large friction effect
Test Pack FPL	Internal stays	Military pack with small lumbar pad and medium friction

To establish a suitable coefficient of friction for input to the model, a short study had to be conducted. Using preset strap tensions and the load cell outputs, the force of friction over the shoulder was determined. Based on the work that MacNeil (1996) performed, the coefficient of friction over the shoulder was calculated using the pulley equation (Equation 1). Initially, the coefficient of friction determined over the shoulder was assumed to be consistent. This assumption was considered acceptable based on the fact that the material used in the shoulder strap was similar to the material used in the waist belt and the lumbar pad for the packs tested.

Once all design parameters were input into the design tool and the body reaction forces (design tool outputs) were predicted, the packs were placed on the mannikin and the body reaction force data was collected. Each pack was removed, replaced, and retested providing three independent trials for each pack. The body reaction forces were averaged over the three trials and compared to the predicted values of the design tool. The error of the predicted values was also calculated, and can be found in section 5.3.

5.3 Validation Results

Test Pack A			
Variable	Average Measures	Design Tool Predictions	Percent Error
T2	143.2	156.1	9.0
T3	0.0	0.0	0.0
F_X	155.3	187.6	20.8
F_Z	4.0	3.9	-3.2
S^N_X	131.1	120.5	-8.1
S^N_Z	306.4	298.7	-2.5

Test Pack B			
Variable	Average Measures	Design Tool Predictions	Percent Error
T2	58.8	62.8	6.8
T3	78.5	76.6	-2.4
F_X	101.0	121.2	20.2
F_Z	126.9	137.8	8.6
S^N_X	63.1	61.7	-2.2
S^N_Z	142.6	130.3	8.6

Test Pack C			
Variable	Average Measures	Design Tool Predictions	Percent Error
T2	76.7	81.2	5.9
T3	0.0	0.0	0.0
F_X	149.3	138.4	-7.3
F_Z	17.5	3.3	-81.2
S^N_X	90.3	82.1	-9.1
S^N_Z	272.3	250.5	-8.0

Test Pack D			
Variable	Average Measures	Design Tool Predictions	Percent Error
T2	91.6	94.2	2.8
T3	29.4	27.6	-6.1
F_X	106.3	146.3	37.6
F_Z	67.4	61.7	-8.5
S^N_X	98.8	91.1	-7.8
S^N_Z	182.8	187.3	2.5

Test Pack Dru			
Variable	Average Measures	Design Tool Predictions	Percent Error
T2	58.6	60.5	3.2
T3	8.2	8.1	-1.2
F_X	175.0	160.7	-8.2
F_Z	45.7	50.6	10.7
S^N_X	108.5	114.7	5.7
S^N_Z	215.6	210.2	-2.5

Test Pack FPL			
Variable	Average Measures	Design Tool Predictions	Percent Error
T2	78.4	75.8	3.3
T3	40.9	40.9	0.0
F_X	180.0	153.6	-14.7
F_Z	108.2	116.9	8.0
S^N_X	95.4	99.4	4.2
S^N_Z	199.4	190.3	4.6

6. Conclusions, Recommendations, and Reservations

6.1. Conclusions

The data collected from the six test packs validated the predictive power of the design tool. A reasonable limit for this type of analysis was assumed to be an absolute value error of ≤10%. All of the output values remained below the 10% error with two exceptions. F_X errors ranged fro n -7.3% to 37.6%. The Tekscan™ system can only provide measurements of the applied force to within 28% of the actual value. It is possible therefore that a large portion of these F_X errors can be attributed to measurement inaccuracy. In this case, the model prediction error may be ≤10%. Further work to better calibrate the Tekscan™ system is ongoing.

In one instance (Pack C) F_Z had an associated error of -81.8%. Clearly this value is unacceptable. However, because of the relatively small magnitude of F_Z in this case, a small discrepancy creates a relatively large error. Furthermore, because all other F_Z values were quite accurately predicted, this error was considered an outlier. The error may also be partially explained due to the nature of the F_Z force. As mentioned previously F_Z is made up of F^L_Z and F^B_Z and their respective contributions to F_Z are not entirely clear (see section 6.2). Despite this F_Z discrepancy, the confidence in the predictive nature of the design tool was still high.

The principal objective of this work is to develop a design tool that can accurately evaluate potential pack designs. Based on the results of this study, the success of this endeavour is partially confirmed. By extending the work done by previous researchers, a novel model of a personal load carriage system was created. That model was validated using a battery of packs on a testing jig. The outputs from the jig confirmed that the output predictions of the model are reasonable However, to extrapolate the model results to the effects on the bearer, a better understanding of the relationship between the strap forces and human threshold values is required.

6.2. Limitations

Despite the fact that the model can accurately predict the body reaction forces of a potential load carriage system and those values can be compared to pain perception levels, precise evaluation remains elusive. Two major challenges exist. First, the relative emphasis that should be placed on each of the attributes that affect comfort is not easily specified. For example, if a system is found to have acceptable F_X scores but highly desirable shoulder reaction scores, should the pack be classified as a desirable or simply acceptable system? Second, it is unclear to what level variations in output values can be detected by human subjects.

Another key reservation, which has already been addressed, is the contribution of F^L_z and F^B_z to F_z. Because of the uncertainty of how each element would contribute to F_z the values of F^L_z and F^B_z were calculated based on known information and in a specific order, F^L_z and then F^B_z. Therefore, during validation, the packs were fitted with a waist belt tension that may be low compared to those of real users. As a result F^B_z may not be contributing to the degree that it would be capable of.

Finally, the relatively poor accuracy of the Tekscan™ measurement device limits the confidence that can be placed in the design model at this point.

6.3. Recommendations

To dispel the reservations of this study further work must be conducted. An evaluation of the waist belt and lumbar pad in isolation would be useful in determining the optimum method for division of F^L_z and F^B_z. Studies with human subjects would be effective in determining a more accurate evaluation technique. The sensitivity of subjects to various pressure points could be determined and the body reaction forces could be weighted accordingly for their respective impact on the design acceptability.

In order to work within the limitations of this study and minimize their impact, a few steps should be taken. Only rely on model outputs that clearly evaluate a pack. For example, if all outputs of a pack exceed pain perception levels then the pack can be considered ineffective. Use the design tool for direct prototype comparisons. However, if one pack exhibits some characteristics that are better, and some that are worse, than a second design, conclusions must be drawn cautiously. It is unclear how much each characteristic contributes to the overall acceptability of a design.

The most effective use of the design tool would be in exposing trends during the design process. Moving certain straps, altering materials, and changing the dimensions of the pack will all affect outputs forces. Understanding how these design parameters affect the body reaction forces would go a long way to deciding which elements of pack design are important and in what direction designers should aim. Sensitivity analysis presented in Section F of the APLCS Phase IV Report illustrates many of the principal design tradeoffs. In that same section, optimization of a function of the output forces, allows the designer to consider the best design parameters with a prescribed set of constraints.

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Appendix A. Pack static equilibrium equations

Pulley equation for shoulder wrap:

$$\frac{T_1}{T_2} = e^{\mu_s \alpha} \tag{A1}$$

Sum of the forces in the X-direction:

$$\begin{aligned} &F_X - T_1 \cdot \cos\theta_1 - T_2 \cdot \cos\theta_2 - W \cdot \sin\beta = 0 \\ &\left[-e^{\mu_s \alpha} \cdot \cos\theta_1 - \cos\theta_2\right] \cdot T_2 + F_X = W \sin\beta \end{aligned} \tag{A2}$$

Sum of the forces in the Z-direction:

$$\begin{aligned} &F_Z + T_1 \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2 - W \cdot \cos\beta = 0 \\ &\left[e^{\mu_s \alpha} \cdot \sin\theta_1 + \sin\theta_2\right] \cdot T_2 + F_Z = W \cos\beta \end{aligned} \tag{A3}$$

Sum of the moments about the centre of gravity:

$$\begin{aligned} &F_X(v_Z - d_3) - F_Z \cdot v_X - T_2 \cos\theta_2 \cdot (v_Z - d_2 - d_3) - T_2 \sin\theta_2 \cdot v_X + T_1 \cos\theta_1 \cdot (d_1 + d_3 - v_Z) - T_1 \sin\theta_1 \cdot v_X = 0 \\ &\left[-(v_Z - d_2 - d_3) \cdot \cos\theta_2 - v_X \cdot \sin\theta_2 + e^{\mu_s \alpha} \cdot \left((d_1 + d_3 - v_Z) \cdot \cos\theta_1 - v_X \cdot \sin\theta_1\right)\right] \cdot T_2 + (v_Z - d_3) \cdot F_X - v_X \cdot F_Z = 0 \end{aligned} \tag{A4}$$

Isolate T_2 by substituting (2) and (3) into (4) and simplifying:

$$T_2 = \frac{W \cdot \left[v_X \cos\beta - (v_Z - d_3) \cdot \sin\beta\right]}{e^{\mu_s \alpha} \cdot d_1 \cdot \cos\theta_1 + d_2 \cdot \cos\theta_2} \tag{A5}$$

Shoulder Reaction Force

$$\begin{aligned} S_X^N &= T_1 \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2 = T_2 e^{\mu_s \alpha} \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2 \\ S_Z^N &= T_1 \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2 = T_2 e^{\mu_s \alpha} \sin\theta_1 + T_2 \cdot \sin\theta_2 \\ S^N &= \sqrt{\left(S_X^N\right)^2 + \left(S_Z^N\right)^2} = T_2 \sqrt{(\cos\theta_2 + e^{\mu_s \alpha} \cos\theta_1)^2 + (\sin\theta_2 + e^{\mu_s \alpha} \sin\theta_1)^2} \end{aligned} \tag{A6}$$

Appendix B. Relationships between variables

$$S_f = T_1 - T_2$$

$$\alpha = 180^\circ + \theta_1 - \theta_2$$

$$e^{\mu\alpha} = \frac{T_1}{T_2}$$

$$S_X^N = T_1 \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2$$

$$S_Z^N = T_1 \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2$$

$$S^N = \sqrt{\left(S_X^N\right)^2 + \left(S_Z^N\right)^2}$$

$$T_{3C} = 2\pi \cdot T_3$$

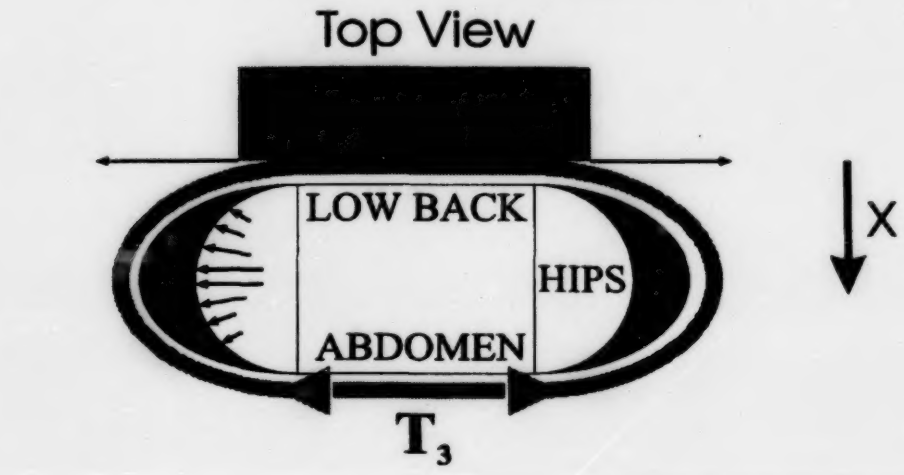
$$F_Z^B = T_{3C} \cdot \cos\gamma_B \cdot (\sin\gamma_B + \mu_B \cdot \cos\gamma_B)$$

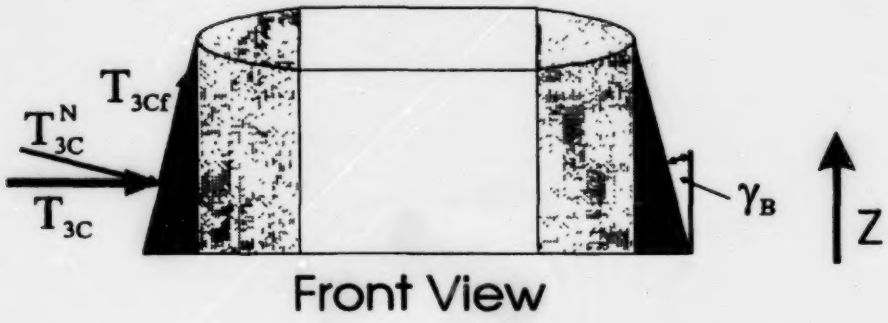
$$F_Z^L = F_X \cdot \cos\gamma_L \cdot (\sin\gamma_L + \mu_L \cdot \cos\gamma_L)$$

$$F_Z = F_Z^B + F_Z^L$$

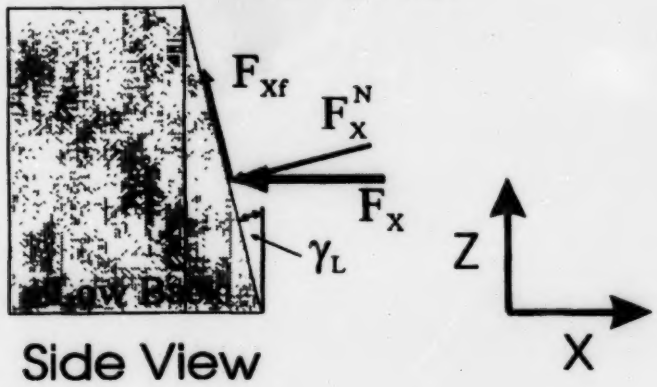
Appendix C. Pack Forces Applied at the Waist

WAISTBELT MODEL





LUMBAR REACTION



Waist Belt Force

Assumptions:

- no net lateral force on pack
- waistbelt connected to pack via pin join, therefore no moment exerted on pack
- no compressive force and "flat" area of abdomen or back

The hoop stress equation approximates the relationship between the tension in the waistbelt and the compressive force on hips, where σ, P, r_H, and t represent the tension in the waist belt, the compressive pressure, the average radius of the "hips" circle, and the thickness of the belt respectively.

$$\sigma_{HOOP} = \frac{P \cdot r_H}{t}$$

$$\text{let } P = \frac{\text{compressive force}}{\text{surface area}} = \frac{T_{3C}}{2\pi \cdot r_H \cdot h_B}$$

$$\text{and } \sigma_{HOOP} = \frac{\text{belt tension}}{\text{cross-sectional area}} = \frac{T_3}{t \cdot h_B}$$

$$\therefore \; T_3 = t \cdot h_B \cdot \left(\frac{T_{3C}}{2\pi \cdot r_H \cdot h_B} \right) \cdot \frac{r_H}{t} = \frac{T_{3C}}{2\pi}$$

Lift due to hip angle (i.e. cone effect) and friction:

$$\begin{aligned} F_Z^B &= T_{3C}^N \cdot \sin\gamma_B + T_{3Cf} \cdot \cos\gamma_B \\ &= T_{3C}^N \cdot \sin\gamma_B + \mu_B \cdot T_{3C}^N \cdot \cos\gamma_B \\ &= T_{3C} \cdot \cos\gamma_B \cdot (\sin\gamma_B + \mu_B \cdot \cos\gamma_B) \\ &= 2\pi T_3 \cdot \cos\gamma_B \cdot (\sin\gamma_B + \mu_B \cdot \cos\gamma_B) \end{aligned}$$

Lift due to Lumbar pad

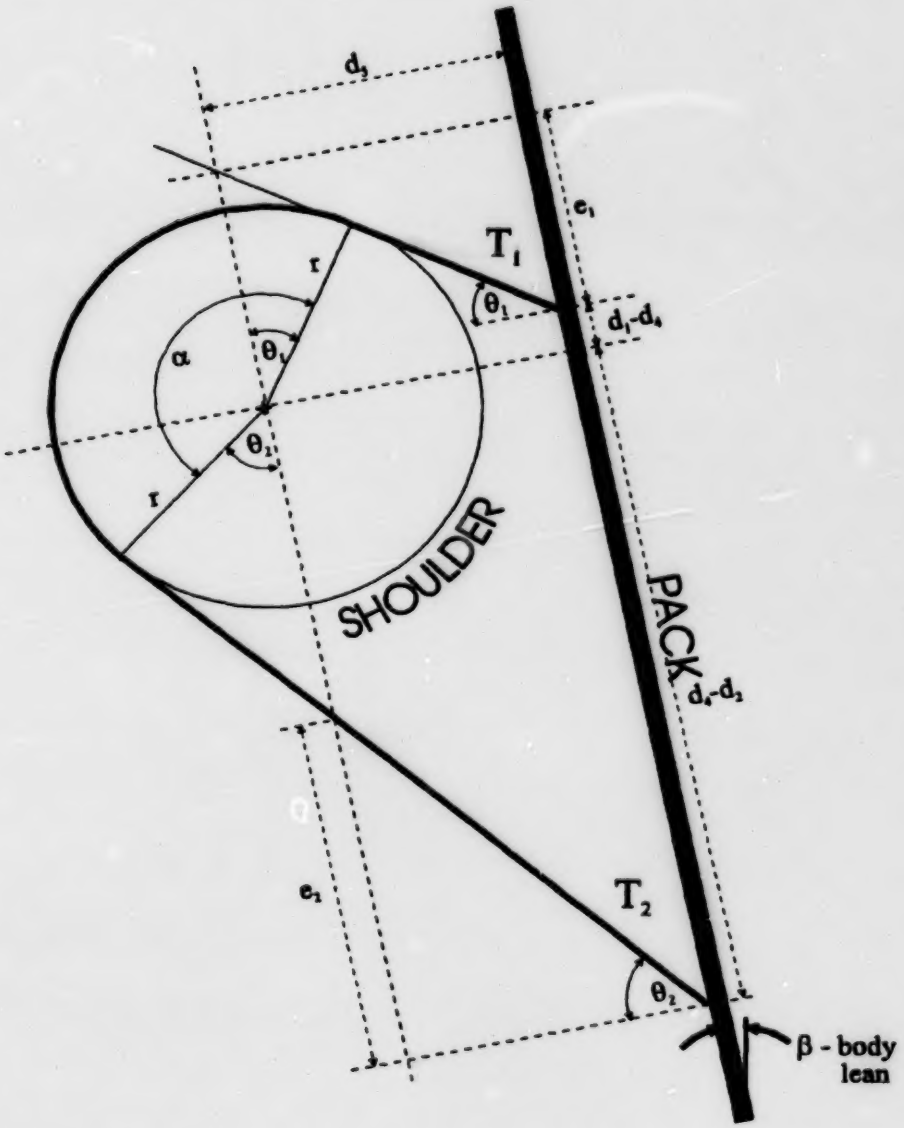
Assumption: lumbar friction at maximum value

$$\begin{aligned} F_Z^L &= F_X^N \cdot \sin\gamma_L + F_{Xf} \cdot \cos\gamma_L \\ &= F_X^N \cdot \sin\gamma_L + \mu_L \cdot F_X^N \cdot \cos\gamma_L \\ &= F_X \cdot \cos\gamma_L \cdot (\sin\gamma_L + \mu_L \cdot \cos\gamma_L) \end{aligned}$$

Total lift at waist

$$F_Z = F_Z^B + F_Z^L$$

Appendix D. Shoulder Wrap Angle Derivation



Shoulder Wrap angle: $\alpha = \pi + \theta_1 - \theta_2$

Top shoulder wrap angle θ_1 **:**

$$\cos(\theta_1) = \frac{r}{(d_1 - d_4) + e_1} = \frac{d_5}{\sqrt{e_1^2 + d_5^2}}$$

$$e_1^2 \cdot (r^2 - d_5^2) + e_1 \cdot 2d_5^2 \cdot (d_4 - d_1) + d_5^2 \cdot \left(r^2 - (d_4 - d_1)^2\right) = 0$$

$$e_1 = \frac{-2d_5^2(d_4 - d_1) - 2d_5 r\sqrt{d_5^2 + (d_4 - d_1)^2 - r^2}}{2(r^2 - d_5^2)}$$

$$\theta_1 = \mathrm{Tan}^{-1}\left(\frac{e_1}{d_5}\right)$$

Bottom shoulder wrap angle θ_2 **:**

$$\cos(\theta_2) = \frac{r}{(d_4 - d_2) - e_2} = \frac{d_5}{\sqrt{e_2^2 + d_5^2}}$$

$$e_2^2 \cdot (r^2 - d_5^2) + e_2 \cdot 2d_5^2 \cdot (d_4 - d_2) + d_5^2 \cdot \left(r^2 - (d_4 - d_2)^2\right) = 0$$

$$e_2 = \frac{-2d_5^2(d_4 - d_2) + 2d_5 r\sqrt{d_5^2 + (d_4 - d_2)^2 - r^2}}{2(r^2 - d_5^2)}$$

$$\theta_2 = \mathrm{Tan}^{-1}\left(\frac{e_2}{d_5}\right)$$

Notes:

- **Quadratic formula with *minus* sign gives Top Wrap Angle**
- **Quadratic formula with *plus* sign gives Bottom Wrap Angle**
- **Either angle may be negative if the attachment point is high enough, but the correct wrap angle α still results.**

Appendix E. Personal Load Carriage System Model Software

E.1 Introduction

This technical note is designed to provide instructions for the operation of the Personal Load Carriage System (PLCS) Model Program. The program was created to provide an easy way to utilize the biomechanical model detailed in this document. It is a series of equations and data manipulations that uses the biomechanical model as its basis to generate the required model outputs. Simply, the program will accept the inputs about an existing pack or proposed pack design and perform the necessary calculations to determine the strap tension required to maintain equilibrium and the contact forces that are later used to evaluate the pack. The details of such analysis are outlined in the main body of this document.

The program is a Microsoft Excel Workbook. This note will outline the technical requirements necessary to operate the program. The note will also go through basic user instructions and simple operating techniques. Finally, some general conclusions are made, commenting on the potential uses of the model and on reservations of the program and model.

E.2 Startup Instructions

The PLCS software is programmed in Microsoft Excel 97. The minimum technical requirements necessary to run the PLCS software are: a personal computer with a 386DX or higher processor, 486 recommended, Pentium preferred. Microsoft Windows 95 or 98 operating system or Microsoft Windows NT Workstations operating system version 3.51 or later. The system will not run on earlier operating system versions.

To access PLCS, use the *Open File* command in Excel, and retrieve the file **PLCSeval.xls**. The interface was designed to fit entirely on one screen, for ease of use. If it is larger than one screen, and the user does not wish to scroll, there are two options for reducing the size. First, the resolution of the monitor may be set to 1024*768 if this is supported by your graphics card (look up "resolution" in the Windows Help system, to see how to do this). Secondly, you may choose a suitable reduction factor for the Excel screen, by selecting the percentage on the pull-down menu on the righthand side of the top toolbar (the window with the size expressed as a percent).

Some of the cells in PLCS are colour-coded to simplify the user requirements, and some cells are locked to prevent inadvertent alterations. The blue cells represent input values related to

pack variables. The green cells are also input values, but they relate to the bearer characteristics, so they are set to defaults values for a 50th percentile male, and can only be changed by unlocking the cells (described below). The beige cells are the output values for strap angles, and predictions of the biomechanical forces.

E.3 Input values

Input values are required for the load, the pack, and the bearer. The relevant dimensions are shown in Figure E1. It is important to note that the pack features are measured relative to the top of the lumbar pad on a generic pack design. In general, this is a well-defined boundary, and provides a suitable reference point for measurements. However, the lumbar pad typically contacts over a substantial surface area, and the biomechanical model assumes a single contact point in the lumbar area. It is reasonable to assume that this is some distance below the top of the lumbar pad, and the laboratory validation exercises have demonstrated that dropping by ⅔ of the lumbar pad height (a_6 in Figure E1) is a suitable value. Since this value of ⅔ is an assumed value, it is included as the variable δ in the spreadsheet, and initialized accordingly, but can be changed by the user.

The variables a_1, a_2, a_3, a_4 and a_5 are used for distances *measured* from the top of the lumbar pad, to distinguish from the d_i variables employed in the force/balance equations (see Figure 11). The d_i values are calculated starting with the corresponding a_i value, by adding or subtracting $\delta * a_6$ to adjust to the lumbar pad contact point. For input of dimensions to the model, the user only needs to enter the a_i values in the spreadsheet, as the rest of the calculations are done automatically.

Six distance measures are required. All the distances can be seen on the diagram in Figure E1 and all measurements should be made in centimeters. Each represents the location of a particular design feature. The first distance measure a_1, is the vertical distance from the top of the lumbar pad to the connection of the upper shoulder strap connection with the pack The second, a_2, is the vertical distance from the top of the lumbar pad to the lower shoulder strap connection. Note that if this connection is below the top of the lumbar pad a negative value is required as input. point. The third, a_3, is the distance from the top of the lumbar pad to the bottom of the pack. This value will be measured down, but should be input in positive values. The fourth, a_4, is a 50th percentile male determination. It is the vertical distance from the centre of the shoulder to the theoretical point at which the top of the lumbar pad should be placed. This value will remain

constant unless other body types are to be tested. The fifth, a_5, represents the distance from the centre of the shoulder to the back face of the pack frame. This measure is currently 14.3cm and is representative of a 50th percentile male and should be left constant unless information about other body types is required. The final measure, a_6, is the total vertical height of the lumbar pad.

The pack name may be entered in the designated area near the top of the worksheet. The other input variables have been discussed in this report. The appropriate units are shown in the spreadsheet. If PLCS is being used for pack design, a typical mass should be entered for W, and variations on this may be studied as part of the sensitivity analysis. The centre of mass may be measured (see Pelot, 1996) for existing packs, and estimated for proposed packs. A reasonable default to begin with is the geometric centre of the pack.

The next three pieces of information to be input are angle measures. Each should be measured and input in degrees. The first, β, is the estimated lean the user may employ to balance the load. The value of 10 degrees is typical and can be used as a constant. The low back angle γ_L of 7 degrees is representative of a 50th percentile male and can be used as a constant. Similarly, the hip angle γ_H, is measured as the anatomical angle of the hips relative to a body fixed vertical axis, and 10 degrees is the default.

The final inputs required are the coefficients of friction produced by the pack material or proposed pack material with the user. These values may be difficult to arrive at and it is recommended that a typical value of 0.125 may be used as an estimate (MacNeil, 1996). However, if independent values are required, the first coefficient μ_s is a general value to be used for the whole pack or more specifically for the contact between the shoulder strap material and the user. The second value μ_L is the coefficient of friction for the lumbar pad with the user, and the third μ_B is the coefficient of friction for the waist belt with the user. Each of these values will be the same if the same material is used throughout or different as the materials are changed.

As mentioned above, for all values which have been set to defaults, the cells are locked. To change any one of these values, put the cursor on the desired cell, then command bar at the top of the spreadsheet, choose *Tools* → *Protection* → *Unprotect Sheet*. All cells can now be modified. To re-lock the cells after modifications, choose *Tools* → *Protection* → *Protect Sheet* and select *OK* in the pop-up window.

E.4 Output values

Once all the inputs have been made, the model will calculate all necessary parameters and output the values of interest. The force outputs are expressed in Newtons. These values are:

- T_1 tension in the top part of the right and left shoulder straps (summed) required for the pack to remain in equilibrium.
- T_2 tension in the bottom part of the right and left shoulder straps (summed) required for the pack to remain in equilibrium.
- T_3 tension required in the waist belt to complete the equilibrium equation as discussed in the body of this document.
- T_{3C} compressive force on the waist, resulting from the tension in the waist belt.
- F_X lateral (i.e. anterior-posterior) force on the lower back.
- F_Z total lift provided by the waistbelt and lumbar pad.
- F_Z^B total lift provided by the waistbelt component.
- F_Z^L total lift provided by the lumbar pad component.
- S^N normal force applied to the shoulder girdle.
- S^N/F_Z ratio of shoulder to waist lift forces.

Some intermediate calculations are required to produce these final results, and these background computations are placed in hidden cells, so that they do not distract from the primary information. To save the information generated while using the PLCS program, save the file with a different name. The original spreadsheet model will remain intact to be used again and the specific information created will be saved for future use.

E.5 PLCS model summary

The model is designed to predict the strap tensions necessary to maintain the pack in a static equilibrium position. The model also predicts the contact forces between the pack and the shoulder and the pack and the lumbar spine. These values have been found to be important in determining the effectiveness of a pack design. Using these values and the main body of text in this report, a prediction of the general effectiveness of a pack can be determined. However, care should be taken before any conclusions are made. The body of this report outlines reservations and makes recommendations on the most appropriate way to use the model output information.

The PLCS Model program was designed for use by the scientific authorities at Defense and Civil Institute for Environmental Medicine. A sample set of information, inputs, outputs, and model calculations is provided in a printout (Figure E2).

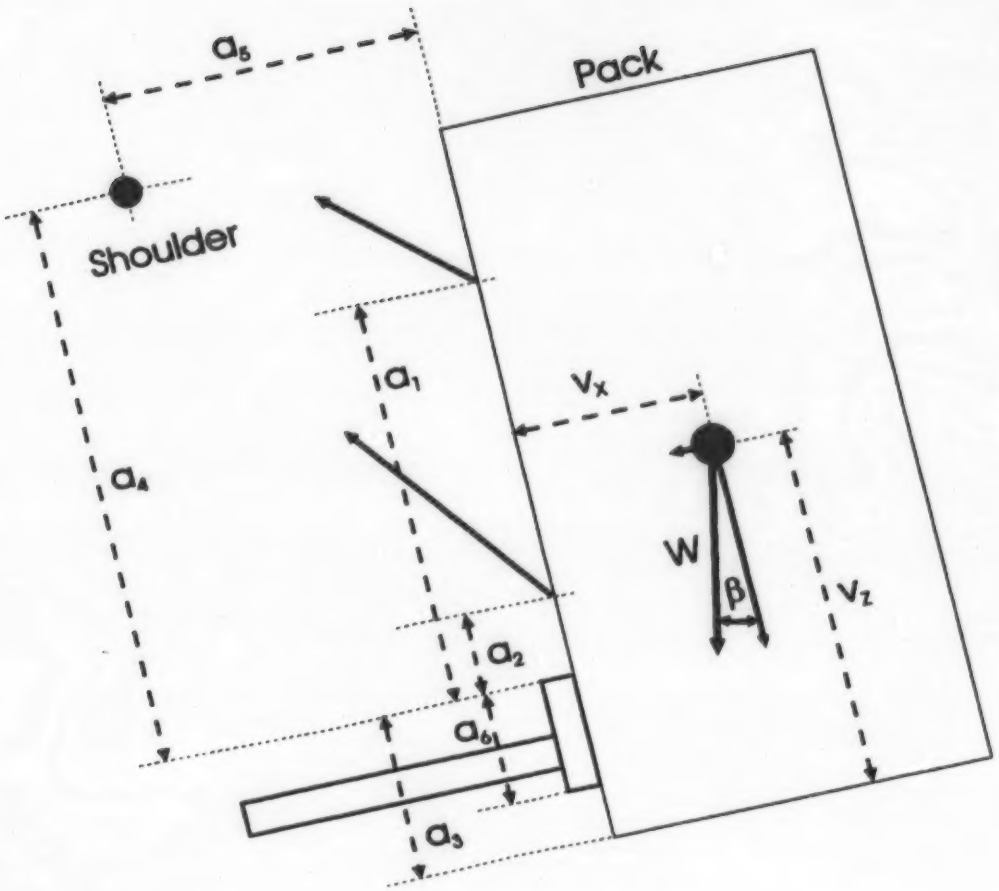
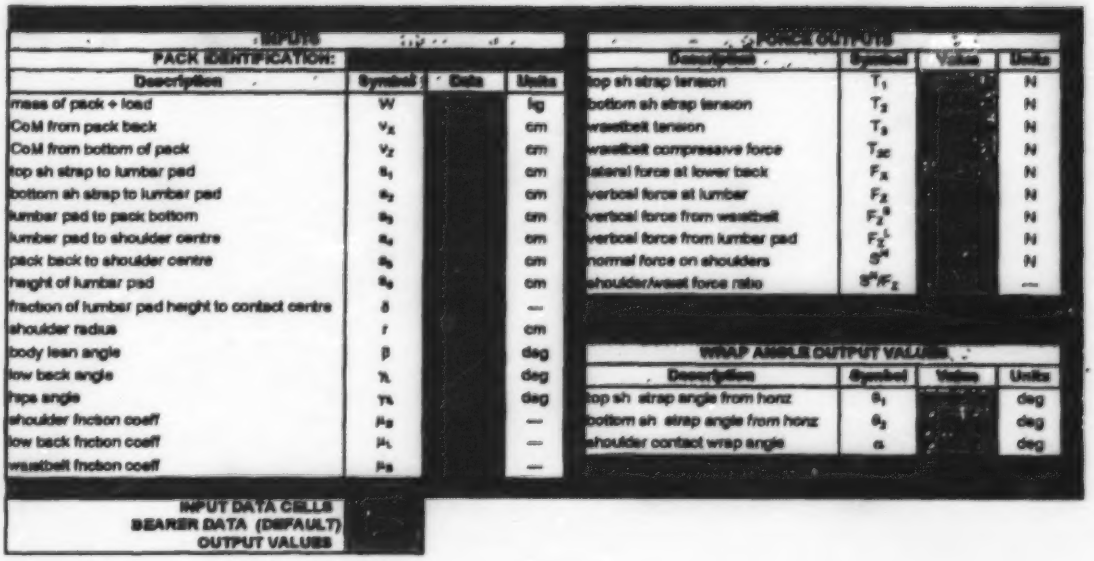


Figure E1. Dimensions for input to PLCS software



INPUTS			
PACK IDENTIFICATION:			
Description	Symbol	Data	Units
mass of pack + load	W		kg
CoM from pack back	v_x		cm
CoM from bottom of pack	v_z		cm
top sh strap to lumbar pad	a_1		cm
bottom sh strap to lumbar pad	a_2		cm
lumbar pad to pack bottom	a_3		cm
lumbar pad to shoulder centre	a_4		cm
pack back to shoulder centre	a_5		cm
height of lumbar pad	a_6		cm
fraction of lumbar pad height to contact centre	δ		—
shoulder radius	r		cm
body lean angle	β		deg
low back angle	γ_L		deg
hips angle	γ_H		deg
shoulder friction coeff	μ_S		—
low back friction coeff	μ_L		—
waistbelt friction coeff	μ_B		—

FORCE OUTPUTS			
Description	Symbol	Value	Units
top sh strap tension	T_1		N
bottom sh strap tension	T_2		N
waistbelt tension	T_3		N
waistbelt compressive force	T_{BC}		N
lateral force at lower back	F_X		N
vertical force at lumbar	F_Z		N
vertical force from waistbelt	F_Z^B		N
vertical force from lumbar pad	F_Z^L		N
normal force on shoulders	S^M		N
shoulder/waist force ratio	S^M/F_Z		—

WRAP ANGLE OUTPUT VALUES			
Description	Symbol	Value	Units
top sh strap angle from horiz	θ_1		deg
bottom sh strap angle from horiz	θ_2		deg
shoulder contact wrap angle	α		deg

INPUT DATA CELLS
BEARER DATA (DEFAULT)
OUTPUT VALUES

Figure E2. Sample PLCS evaluation worksheet

DOCUMENT CONTROL DATA SHEET

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1b. PUBLISHING AGENCY DCIEM	

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14. ABSTRACT

(U) The backpack is the military personnel's device of choice for load carriage. Until recently, little was done in Load Carriage System (LCS) research and development. However, the recent recreational boom has seen the basic backpack design undergo much manipulation. The most notable change has been the addition of a load bearing waist belt.
Deciding if design changes were effective usually meant building a prototype and obtaining human feedback on various characteristics. This method is costly and time consuming and the results are subjective. Defence and Civil Institute for Environmental Medicine requires a more efficient and effective means of evaluating preliminary pack designs.
Therefore, the purpose of this study was to develop a personal load carriage system design tool. An appropriate evaluation tool should enable designers to input pack parameters and receive an objective measure of the pack's effectiveness. Pack parameters include the pack dimensions, weight, centre of gravity, and location of shoulder straps, waist belt, and lumbar pad. The objective evaluation consists of two body reaction forces known to relate to pack acceptability scores. With knowledge of the body reaction forces one gains an understanding of comfort, and can compare potential prototypes.
A statically determinate model of the pack-person interface was developed to include the design parameters of interest and the evaluated body reaction forces. From the design inputs, the model determines the remaining pack geometry. The equilibrium equations and pack variable relations determine the tension of the pack straps, while the force couples between the torso and the pack are used to calculate the body reaction forces.
Stevenson et. al. (1995) determined human pain perception levels for the shoulder and lumbar contact forces. These values were used to provide an understanding of the degree of the body reaction forces.
To validate the effectiveness of the design tool, six packs were tested on a human form jig. The jig was instrumented to measure the required body reaction forces. The required design parameters of each pack were measured and used as inputs to the model. The model detailed the way in which each pack was to be setup and three independent data sets were collected. The data showed that the design tool was able to predict outputs to within 10% of the measured values.
Despite the fact that the body reaction force predictions were validated, reservations exist about the evaluative ability of the design tool. It is unclear which of the body reaction forces has the greatest impact on the acceptability rating of a pack. Therefore, it becomes difficult to differentiate between a pack which has a high shoulder reaction force and low lumbar force, from a pack with low shoulder forces and high lumbar forces. The ability of human subjects to detect changes in the body reaction forces in unclear.
The vertical force contribution of the lumbar pad and the waist belt is not well understood. The total lift of the waist belt/lumbar pad complex is well understood and was validated. However, the exact contribution of each element is unclear.
In order to work with the limitations of this design tool the outputs should be used to understand the trends associated with parameter variation. As well, design that produce body reaction forces above the pain perception levels should be considered inappropriate.

French abstract not available.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) biomechanics; biomechanical model; load carriage; backpack

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